Extrasolar Terrestrial Planets on Stable Resonant Periodic Orbits

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Introduction

The recent success of the radial velocity technique in detecting more than 100 extrasolar planets has created rich grounds for the extension of the theories of the formation and dynamical evolution of our solar system to other planetary systems. Such an extension allows planetary scientists to explore the possibility of the existence of habitable planets among extrasolar planetary systems. It is therefore of great importance to explore whether such planets can exist on stable orbits in the habitable zones of their central stars, and also whether their orbits will be stable for long enough duration of time to allow the development of life.

In multi-body planetary systems, such orbits correspond to mean-motion resonances. When the geometrical configurations of such orbits are periodically repeated, they are known as "**Resonant Periodic Orbits**". Resonant periodic orbits (RPO) are quite common in our solar system. For instance, Jupiter and Saturn rotate around the Sun on orbits that correspond to a (5:2) mean-motion resonance.

With discovery of extrasolar planets, RPOs are no longer exclusive to our solar system. For instance, GJ 876 contains two planets in a (2:1) resonance and the system of 55 Cnc shows a (3:1) commensurability between its two innermost planets. These all indicate that it is of great value to study the possibility of existence and also the stability of resonant periodic orbits for different resonances. In this paper, we present the result of our extensive numerical study of the existence and the stability of different resonant periodic orbits, and present a methodology for searching the parameter-space of multi-body systems for regions where resonant periodic orbits can be stable.

Numerical Analysis

We studied the orbit of the outer body of a three-body system for different values of the mass-ratio of the inner planet and the central star, μ, and also different values of the orbital eccentricity of the inner planet, e. We performed an extensive initial numerical search for 1:2 resonant periodic orbits for several mass-ratios and orbital eccentricities of the inner planet. Once an RPO was found, we varied μ and e systematically (continuation process) and studied the stability of the orbit of the outer body.

Figure 1 shows the overall results of the continuation process for starting values of $\mu = 0.001$ and $e = 0.1$. As shown here, for the same orbit of the inner planet, there can be several RPOs with different orbital elements on different branches. These branches are labeled according to the initial values of the quantities

$$h' = e \cos \varpi \qquad\qquad k' = e \sin \varpi$$

where ϖ is the longitude of the pericenter of the outer body. For instance, the branch labeled as $h'52k'16$ represents the result of continuation started from a resonant periodic orbit with $h' = 0.52$ and $k' = 0.16$. Such an orbit has an eccentricity equal to 0.544 and a longitude of pericenter equal to 17.1 degrees.

Figure 1

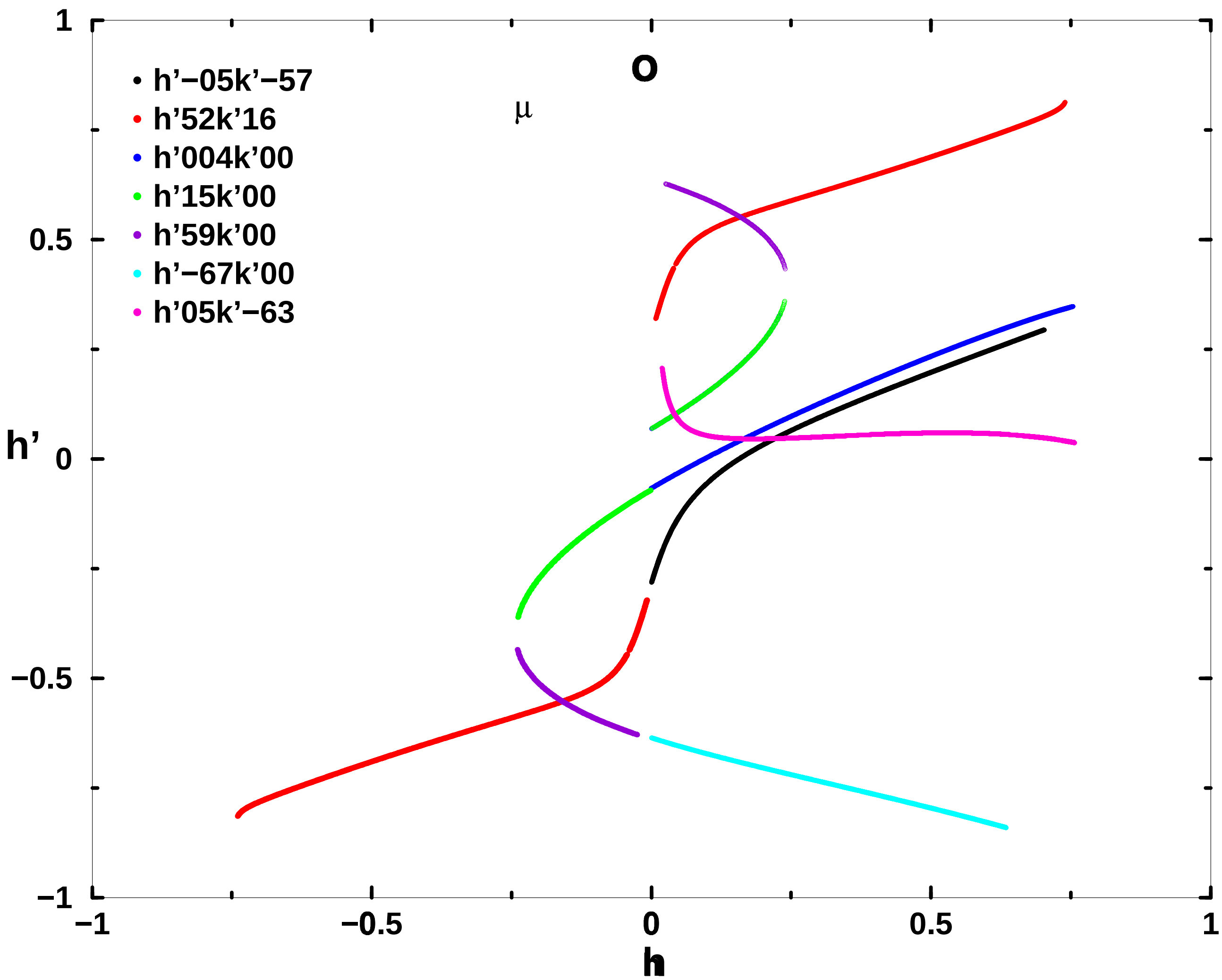
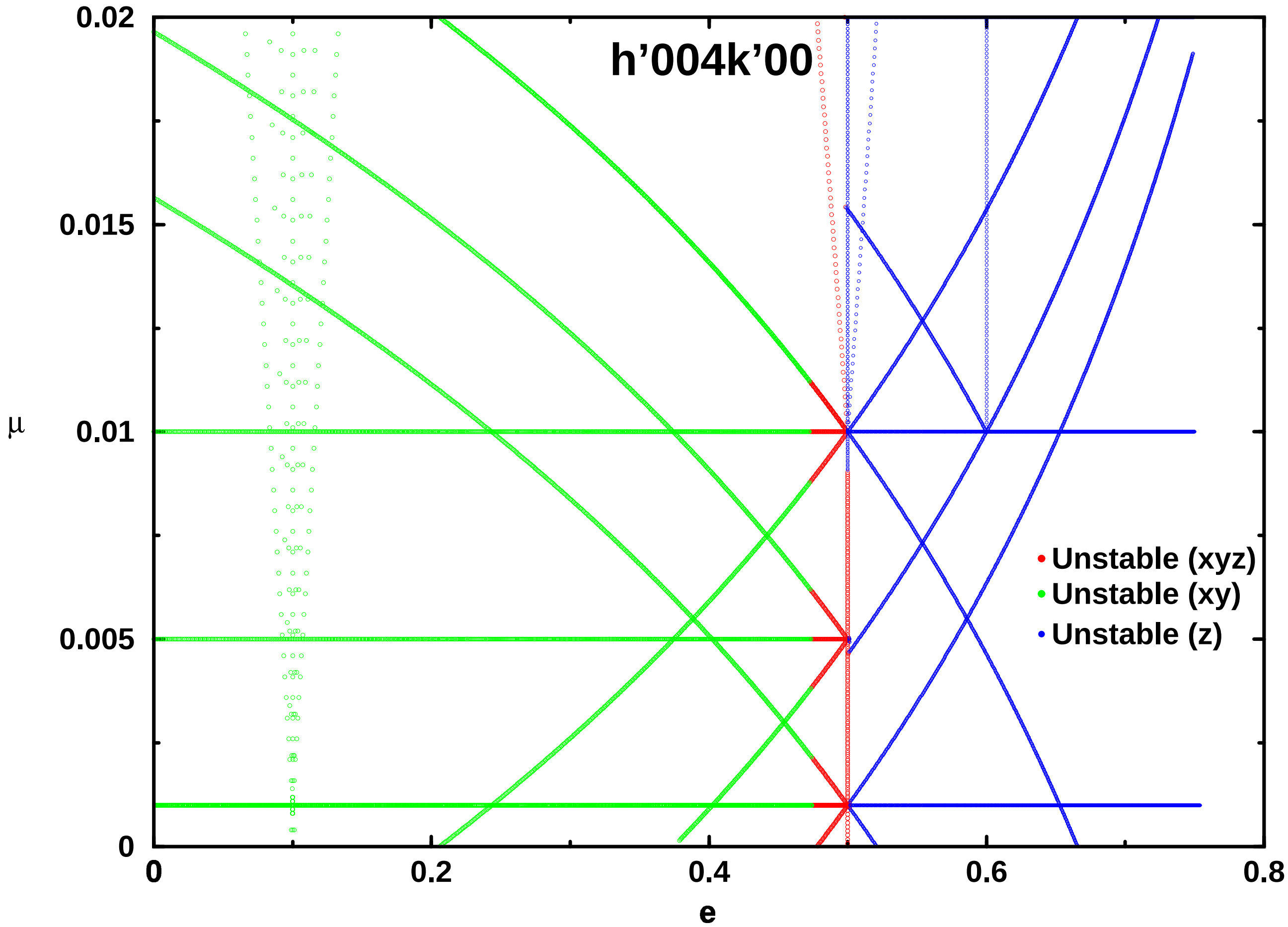


Figure 2



We also studied the phase-parameter space of the system, in search of regions corresponding to stable resonant periodic orbits, for all different branches of Figure 1. In most cases, the RPOs were unstable. Figure 2 shows a criss-crossing of the (μ, e) space with continuation paths of the RPO designated as $h'004k'00$. An interesting feature of this case is that the RPO can be stable in the horizontal directions while unstable in the vertical one. We note that planar motions, such as the RPOs in this study, can be unstable to vertical perturbations.

Figure 3

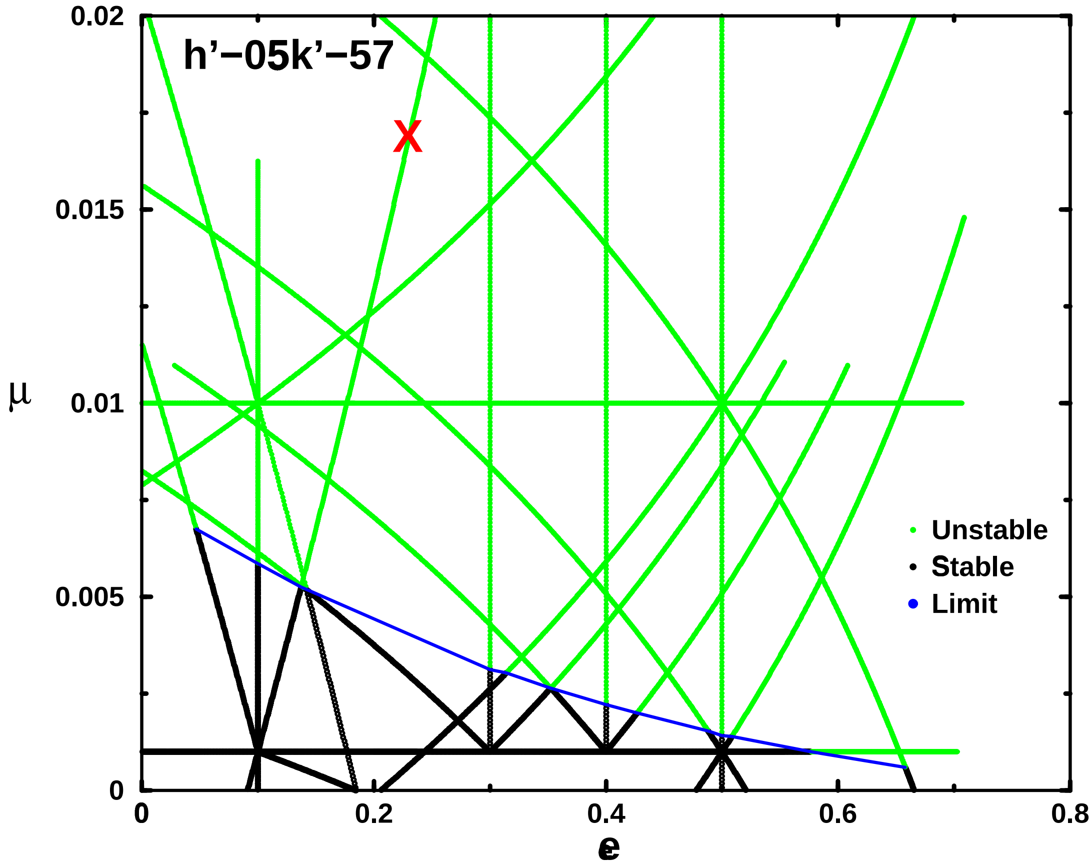
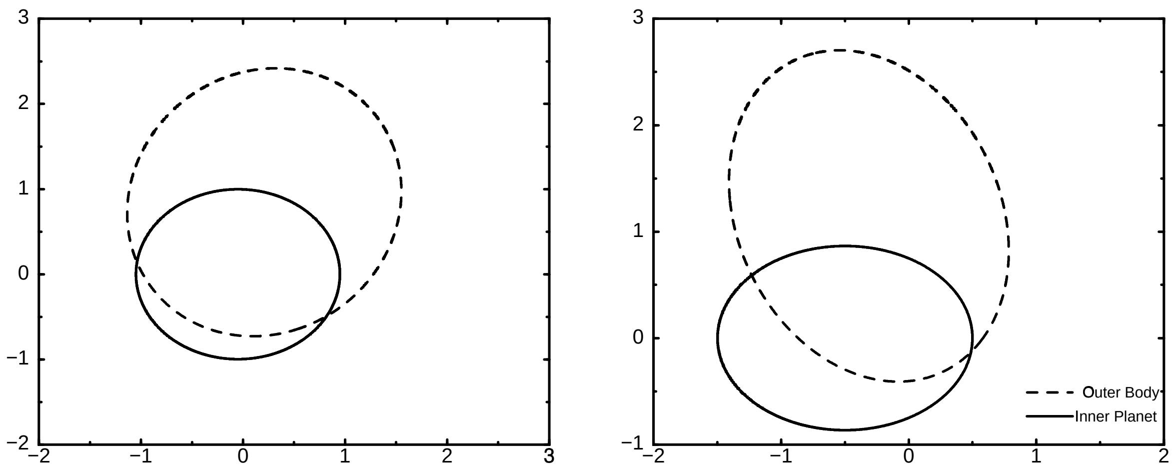


Figure 3 shows similar criss-crossing analysis for the continuation branch of the RPO $h' - 05k' - 57$. The system, in this case, reveals a region of stability with a distinct boundary from its large region of instability. As shown here, the orbit of the outer planet is stable along the horizontal line of $\mu = 0.001$, for all values of the orbital eccentricity of the outer planet less than 0.57. Along a vertical line such as $e = 0.5$, the system is stable for all values of the mass-ratio less than 0.0014. Figure 3 also shows that at higher values of the eccentricity of the inner

Figure 4



planet, the stability of the system requires lower mass-ratios implying that the RPOs of a system with a more massive inner planet in a 1:2 exterior resonance are most stable when the orbit of the inner planet is closer to a circular orbit.

Figure 4 shows the different RPOs of the system for the mass-ratio of 0.001, and different values of the inner planet's orbital eccentricity ($e = 0.05$ left, $e = 0.5$ right). It is worth noting that for these stable orbits, the pericenter directions of the inner and outer planets are not aligned. The existence of a similar asymmetry of stable RPOs has also been suggested in the context of the Galilean satellites.

Conclusions

Our approach in this paper toward the understanding of orbital resonances provides fundamental information on their structures. Stable periodic orbits are centers of librations whose periods are also obtained, at least for small amplitudes, from our stability computations.

We examined the phase-parameter space of the system for different values of the mass-ratio and the orbital eccentricity of the inner planet. In the majority of the cases, the RPOs were unstable. We were, however, able to show that stable resonant periodic orbits can be found when the mass and the orbital eccentricity of the inner planet are within a certain range (Figure 3).

Our initial search for RPOs also covered the internal 2:1 resonance. We have not found any RPOs, either stable or unstable, in this case. The apparent lack of RPOs in the internal 2:1 resonance also raises questions regarding the same resonance in the full three-body system, i.e., when the mass of the outer body is non-zero. As the latter increases and the mass of the inner body decreases, the system passes from external resonance to internal. Along the way, one should find the limits of masses for which stable RPOs exist. Such studies will have immediate applications to some of the recently discovered extrasolar planetary systems such as GJ876 in which two planets are locked in a near 1:2 resonance.